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On the Trend of Improvement of Thermal Model for Calculating the TOT and HST

***Abstract**. As the transformers are one of the expensive equipment of power systems optimum loading is notified by designers, nowadays loading was done base on the IEC and IEEE standards according to the hot spot temperature (HST) as an effective criteria on loading and overloading. To predict HST and TOT, many principal models have been proposed such as classic thermal, alternative thermal and dynamic thermal models. In this paper attempts have been made to introduce reliable and acceptable thermal models, and explain the procedure of calculating the top oil temperature and hot spot temperature as two criteria to evaluate the load ability and the insulation life of transformer. Eventually, different types of thermal models are compared with each other on a 30-MVA oil-natural air-forced transformer.*

***Streszczenie.** W artykule zaproponowano sposób tworzenia modelu termicznego transformatora, oraz opisano procedurę obliczania maksymalnej temperatury oleju i uzwojeń. Te dwie wartości zdefiniowano jako parametry określające dopuszczalną obciążalność i żywotność izolacji transformatora. Dokonano porównania różnych modeli termicznych, stworzonych na podstawie 30 MVA transformatora z olejem naturalnym i wymuszonym obiegiem powietrza. (**Modyfikacje i ulepszenia modelu termicznego transformatora na potrzeby obliczeń parametrów TOT i HST**)*

Keywords: oil immersed transformer, ambient temperature, HST, thermal model
Słowa kluczowe: transformator olejowy, HST, model termiczny

Introduction

Power transformers are one of the most expensive components in an electricity system. Knowing their optimum loading capability is essential to meet the goals of maximizing return on investment and lowering the total cost associated with transformer operation. The transformer winding hot-spot temperature is one of the most critical parameters when defining the power transformer thermal conditions and overloading capability beyond the nameplate rating [4-6].

Loading and overloading of power transformer beyond their nameplate rating depends on several factors including the design and operating characteristic of transformer, daily load curve, historical loading data, testing and maintenance program, and particular applications. Traditionally, transformer overloading capabilities are determined by the winding "hottest- spot" temperature. Determining accurately the hottest-spot temperature is very critical to the overall life expectancy assessment [7-9].

Thermal models

Several models have been proposed that can be used for predicting transformer thermal behavior. These are as follow [13-21]:
The ANSI Top-oil-rise model
The Top-oil model
The semi-physical model
Pierce's model
Swift's model
Other models

I. Top Oil Rise Model

This model is presented in IEEE Loading Guide of the IEEE C57.91. standard which is a function of the load and load loss ratios [15]. In this model the thermal behavior of transformer is estimated as a first order model, in which the top-oil-temperature rise over ambient temperature is governed by the differential equation as in equation (1) [15, 26].

$$T_0 \frac{d\theta_0}{dt} = -\theta_0 + \theta_u \tag{1}$$

Which solution is an exponential function of,

$$\theta_0 = (\theta_u - \theta_i)(1 - e^{-(\frac{t}{T_0})}) + \theta_i \tag{2}$$

where: θ_0 Top-oil rise over ambient temperature (°C), θ_u Ultimate top-oil rise for load L (°C), θ_i Initial top-oil rise for t=0 (°C), T_0 Time constant (hrs), t duration of load(hrs),
For

$$\theta_u = \theta_{fl} \left[\frac{I_{pu}^2 R + 1}{R + 1} \right]^n \tag{3}$$

$$T_0 = \frac{C\theta_{fl}}{P_{fl}} \tag{4}$$

$$I_{pu} = \frac{I}{I_{rated}} \tag{5}$$

Lesieutre et al. have proved the low accuracy of this model, as the comparison of estimated coefficients and measured TOT values demonstrated to be obviously different between each other[27-30].

I the specified load,
I_{rated} the rated load,
I_{pu} the ratio of specified load to rated load,
P_{fl} the total loss at rated load (watts),
R the ratio of load loss to no-load loss at rated load,
C the thermal capacity (Wh/ ^{o}C).
n Oil exponent—(an empirically derived coefficient selected for each cooling mode to approximately account for change in resistance with load),

II. Top-Oil Model

Top-oil model were proposed by [22, 28, 31]. Later, they suggested an improved model rather than the top-oil-rise model by incorporating ambient temperature variations into this model. This improvement is based on the differential equation given by (6).

(6) $$T_0 \frac{d\theta_{top}}{dt} = -\theta_{top} + \theta_{amb} + \theta_u = f(\theta_{top}, \theta_{amb}, \theta_u)$$

This has the solution of[10],

(7) $$\theta_{top} = (\theta_u + \theta_{amb} - \theta_{topi})(1 - e^{-(\frac{t}{T_0})}) + \theta_{topi}$$

To predict and estimate of the top oil temperature by discrete measured data, as it has been elaborated on prior to this section, Euler method has been used. And (8) becomes[31, 32]:

(8) $$\theta_{top}(k) = \frac{T_0}{(T_0 + \Delta t)} \theta_{top}(k-1) + \frac{\Delta t \theta_{fl}}{(T_0 + \Delta t)} \left[\left(\frac{I^2(k)(R+1)}{(R+1)} \right) \right]^n + \frac{\Delta t}{(T_0 + \Delta t)} \theta_{amb}(k)$$

By assuming n=1, equation (8) is accountable by linear regression as:

(9) $$\theta_{top}(k) = K_2 \theta_{amb}(k) + \left[K_1 \right] I^2(k) + (1 - K_2)\theta_{top}(k-1) + \left[K_3 \right]$$

Where:

(10) $$K_1 = \frac{\Delta t R \theta_{fl}}{(T_0 + \Delta t)(R+1)}$$

(11) $$K_2 = \frac{\Delta t}{(T_0 + \Delta t)}$$

(12) $$K_3 = \frac{\Delta t \theta_{fl}}{(T_0 + \Delta t)(R+1)}$$

III. The Semi Physical Model

A semi-physical model is often used as a physical model and is described to be inaccurate. By substituting 1-K2 in (9), and changing the notation used in the equation, equation (13) can be obtained [28-30]. More variables meaning that a smaller sum-square error between measured and predicted top oil temperature can be achieved [5, 28, 32].

(13) $$\theta_{top}(k) = K_1 \theta_{top}(k-1) + K_2 \theta_{amb}(k) + \left[K_3 \right] I^2(k) + \left[K_4 \right]$$

where, $K_1 = \frac{T_0}{(T_0 + \Delta t)}$, $K_2 = \frac{\Delta t}{(T_0 + \Delta t)}$, $K_3 = \frac{\Delta t R \theta_{fl}}{(T_0 + \Delta t)(R+1)}$, $K_4 = \frac{\Delta t \theta_{fl}}{(T_0 + \Delta t)(R+1)}$

IV. IEEE Alternative Thermal Model

Investigations, performed by Pierce and others in 1992, have revealed that during overloads there is a time lag between the top-oil temperature rise and the oil temperature rise in the winding cooling ducts [14, 33, 34]. This phenomenon results in the HST in windings that may be greater than the HST predicted by the IEEE loading guide equations. Pierce suggested improved equations, Annex G, which accounts for the type of liquid, cooling mode, winding duct oil temperature rise, resistance, viscosity changes, stray losses, eddy current losses, ambient temperature and load changes during a load cycle. This model characterizes the thermal dynamic process in transformers using three different first-order equations, the first associated with windings, the second associated with the hot spot and the third associated with the bulk oil. This nonlinear model should be more accurate in TOT and HST prediction than those simplified linear models. However, using this model requires that both top and bottom temperatures be measured and that many transformer parameters, not usually available in the manufacturing transformer test report be used. Therefore, it is difficult to put the Pierce model into practical application [13, 18, 29, 31, 32]. In summary, the required data for each of the thermal models of IEEE standard has been discussed above, and the classic model (Clause7) and alternative model (Annex G), are presented in Table 1.

Table 1.Required data for IEEE thermal models

IEEE Classical Model (Clause7)	IEEE Detailed (Annex G) Model
1. Top-oil temperature rise at rated 2. Hottest-spot temperature rise over top-oil at rated load rated load 3. Loss ratio at rated load 4. Winding time constant 5. Oil time constant or • Weight of core & coil rated load • Weight of tank & fittings • Gallons of fluid 6. Type of cooling system tested rating	1. Top-oil temperature rise at rated 2. Hottest-spot temperature rise over top-oil at rated load rated load 3. Average winding temperature rise at rated load 4.Bottom oil temperature rise at rated load 5. Losses data from test report • KVA base of test data • Winding temperature rise • Winding losses • Winding eddy current losses • Stray losses • Core losses 6. Weight of core & coil 7. Weight of tank & fittings 8. Gallons of fluid 9. Type of cooling system 10. Type of winding material 11. Winding time constant 12. Location of hottest spot 13. Per-unit eddy current losses at hottest-spot location

Thermal-Electrical Model (Dynamic Thermal Model)

Thermal-electrical model of a transformer based on the principals of heat transfer theory has been offered by Swift for the first time [17, 35-38] and then Susa introduced improved model by assuming the non-linear thermal oil resistance based on swift's approach. The variations of viscosity with temperature were included in this model [17, 20, 39-43].Reviewing the thermal-electrical model has begun by the energy balance equation given as, [12, 17, 21, 44].

(14) $$q = C_{th} \times \frac{d\theta}{dt} + \frac{\theta - \theta_{amb}}{R_{th}}$$

where: q is the heat generation, C_{th} is the thermal capacitance, θ is temperature, R_{th} is the thermal resistance, θ_{amb} is the ambient temperature.

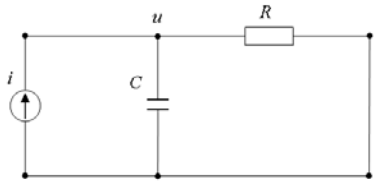

Fig. 1.a. An electrical RC circuit

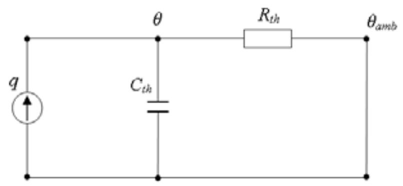

Fig. 1.b. The analogous thermal circuit

By defining the simple electrical RC circuit, as shown in Figure 1.a and Figure 1.b, the following equation can be written:

$$i = C_{el} \times \frac{du}{dt} + \frac{u}{R_{el}} \tag{15}$$

where: i is the electric current, C_{el} is the electrical capacitance, R_{el} is the electrical resistance, u - is the electrical voltage.

By comparing equations (14) and (15) the analogy between electrical and thermal processes is obtained, as presented in Table 2 [21, 45].

As it has been indicated the thermal resistance and capacitance can be explained as two elements to resist heat flow and store heat [14, 46, 47].

Table 2. Thermal-Electrical analogy

Thermal		Electrical	
Generated heat	Q	Current	i
Temperature	Θ	Voltage	u
Resistance	R_{th}	Resistance	R_{el}
Capacitance	C_{th}	Capacitance	C_{el}

Top Oil Temperature Model

Depending on the heat transfer theory and thermal-electrical analogy, the top oil temperature model is offered as a thermal circuit, as in Figure 2 [21, 29, 40].

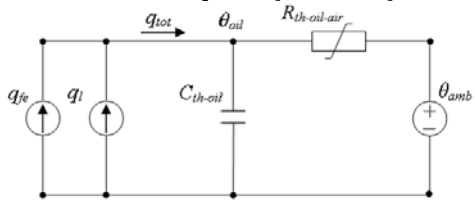

Fig. 2. Top-oil temperature model

In the thermal circuit, Figure 3, load and no load losses of the transformer are indicated with two ideal heat sources, and the ambient temperature has been represented with an ideal temperature source[17, 39].

A differential equation could be derived as follows:

$$q_{fe} + q_l = C_{th-oil} \times \frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil} - \theta_{amb})}{R_{th-oil-air}} \tag{16}$$

The existence of oil viscosity variation is based on temperature and its effect on oil thermal resistance and top oil time constant can be used to distinguish this model from other thermal models[36, 48].

The Hot Spot Temperature Model

According to the conventional heat transfer theory that was given for the top-oil temperature model and the non-linear thermal resistance, the hot-spot temperature model can be calculated as a thermal circuit, Figure 4[17, 40]. The nonlinear thermal resistance $R_{th-hs-oil}$ has been explained according to the heat transfer theory. This nonlinear thermal resistance from winding to oil includes thermal resistance of winding, insulation, and oil. By comparing these thermal resistances it has been shown that the thermal resistance of oil is more than other thermal resistances; therefore the final thermal resistance has been calculated as follows [20, 49, 50]:

$$R_{th-hs-air} = R_{th-air} = \frac{1}{h \times A} \tag{17}$$

And h can be defined as,

$$h = C_1 \times \left(\frac{\Delta\theta_{hs}}{\mu}\right)^n \tag{18}$$

Based on Figure 3 the related differential equation for this thermal circuit has been given:

$$q_{cu} = C_{th-wd} \cdot \frac{d\theta_{hs}}{dt} + \frac{(\theta_{hs} - \theta_{oil})}{R_{th-hs-oil}} \tag{19}$$

By substituting the heat transfer coefficients (21) and (22) into equation (19) the following equation has been obtained [17, 43, 51]:

$$q_{cu}\left(\frac{\mu^n}{C_1.A}\right) = \left(\frac{\mu^n}{C_1.A}\right) \times C_{th-wd} \times \frac{d\theta_{hs}}{dt} + (\theta_{hs} - \theta_{oil})^{n+1} \tag{20}$$

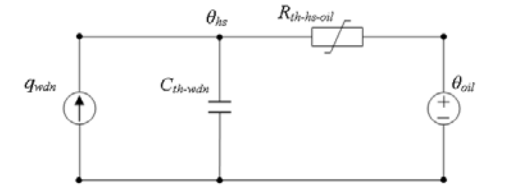

Fig. 3. The hot spot temperature model

Example of Results

As seen in previous sections, different types of thermal models are introduced. The trend of improvement from the classic thermal models to dynamic ones indicated that the dynamic thermal model can predict hot spot temperature more accurate than some more other models. Base on this claim, these models have been employed for 30-MVA transformer.

These transformers have three thermometers to indicate the top oil temperature and winding temperature for high and low voltage windings. In order to collect the required data such as TOT and ambient temperature, the use of the thermometers and its connection to data logger has been suggested. The suggested connection of the equipment to the transformer is shown in Figure 4.

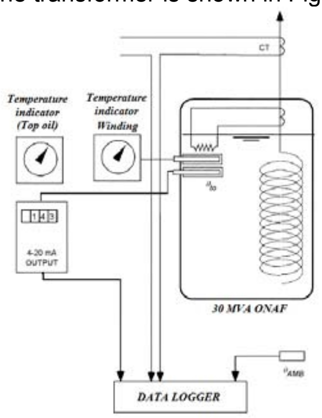

Fig 4. Method for instrumentation

Then, the TOT and HST have been calculated by using classic and dynamic thermal models. According to IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers-C57.91-1995, when the hottest spot temperature is greater than $110°C$ values of FAA, it will be more than 1. It is suggested that FAA to be kept less than 1 due to normal life extension. As this relate to hottest spot temperature, it indicates that the HST should be kept less than $110°C$. Figure 5 indicates the results for 30-MVA transformer, compares the top oil temperatures that are calculated based on Runge-Kutta method for both thermal models, classic and dynamic thermal models. Similarly, comparison of hot spot temperatures for classic and dynamic thermal models for 30-MVA transformer has been shown in Figure 6. Also, the comparisons of TOT and HST achieved from these two types of thermal models for 250-MVA transformer have been displayed in figure 8, and 9 respectively.

Eventually, to interpret the following figures which are given for HST and TOT of cases of our study the loss of life of them are calculated according to IEEE C57 equations. Then evaluate the error of LOL for each of the thermal models. Table 3 gives the error (%) of Loss of life of the 30-MVA transformer for dynamic and classic thermal models. Based on these results, the dynamic thermal model gives less error than classic thermal model.

Table 3. Error(%) for LOL for thermal models

TX	Dynamic Thermal model	Classic Thermal model
30 MVA	4.1×10^{-3}	1.2576

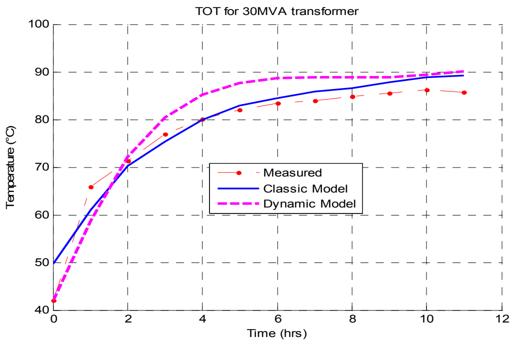

Fig 5. Comparison of TOT for 30-MVA transformer

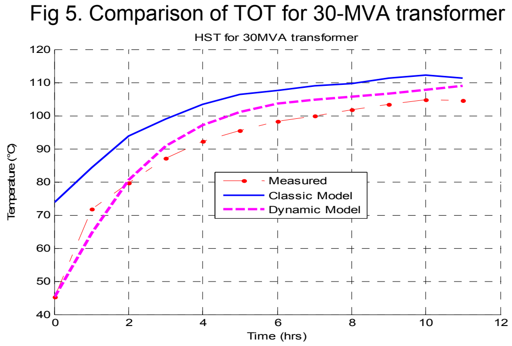

Fig 6.Comparison of HST for 30-MVA transformer

Conclusion

The trend of improvement of thermal models began from the top oil rise model that was recommended by IEEE C57-1991. The simplified top-oil-rise model has the limitation that it does not accurately account for the effects of ambient temperature dynamics on TOT. Lesieutre et al. proposed an improved model over the top-oil-rise model by incorporating ambient temperature variations into the model.

Investigation, performed by Pierce and others in 1992, has shown that during overloads there is a time lag between the top-oil temperature rise and the oil temperature rise in the winding cooling ducts. This phenomenon results in the HST in windings that may be greater than the HST predicted by the IEEE loading guide equations. Pierce proposed improved equations, available in Annex G IEEE C57.91-1995 that accounts for type of liquid, cooling mode, winding duct oil temperature rise, and resistance and viscosity changes. However, using this model requires that both top and bottom temperatures be measured and that many transformer parameters, not usually available in the manufacturing transformer test report be used. Therefore, it is difficult to put the Pierce model into practical application. Swift et al. proposed thermal model based on heat transfer theory. More, Susa introduced improved model by assuming the non-linear thermal oil resistance and the variation of viscosity with temperature were included in this model. In this paper attempts have been made to introduce reliable and acceptable thermal models, and explain the procedure of calculating the top oil temperature and hot spot temperature as two criteria to evaluate the load ability and the insulation life of transformer.

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